

Scaling New Heights:  
The Challenge of  $K_L \rightarrow \pi^0 \nu \bar{\nu}$

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# Scaling New Heights: The Challenge of $K_L \rightarrow \pi^0 \nu \bar{\nu}$

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## Outline

- CP violation and flavor physics
- Role of kaon decays
- KOPIO experiment
  - Concept
  - A look at some detector subsystems
- Conclusion and outlook

# Introduction

40th anniversary of the discovery of CP violation.

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PHYSICAL REVIEW LETTERS

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## EVIDENCE FOR THE $2\pi$ DECAY OF THE $K_2^0$ MESON\*†

J. H. Christenson, J. W. Cronin, ‡ V. L. Fitch, ‡ and R. Turlay §

Princeton University, Princeton, New Jersey

(Received 10 July 1964)

What have we learned since? To gain some perspective, interesting to look at the halfway point (mid 80's), from a classic textbook:<sup>a</sup>

“CP violation in  $K_L^0$  decay may be caused by one (or more) of the following:”

- “millistrong”:  $\sim 10^{-3}$  T or C violation in the strong interaction
- $\sim 0.1 - 0.01$  T or C violation in the hadronic EM interaction
- “milliweak”:  $10^{-3}$  T violation in the weak interaction
- “superweak”:  $\Delta S = 2$  interaction of order  $10^{-10} G_F$
- CP-violating phase in quark flavor mixing
- extra CP-violating Higgs, LR-symmetric models, heavy bosons, etc. etc.

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<sup>a</sup>Commins and Bucksbaum, *Weak Interactions of Quarks and Leptons* (1983)

# Where are we today?

- CKM phase is the dominant source of CP violation (at least where we have seen it so far, i.e. flavor-changing processes)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Interplay of quark mixing and CP violation leads to a rich phenomenology. Study of CP-conserving processes can shed light on CP violation.
- New era with the advent of B factories. CP violation finally observed outside kaon system. CKM picture confirmed (unfortunately?).
- Can we understand the CKM matrix structure in a deeper way?
- Cosmological connection (baryon asymmetry) highlights fundamental importance of CP violation in a very “real” way.
- Are there other sources of CP violation in quark sector? EDM’s? (or elsewhere: neutrinos?)
- Personal bottom line: CP violation is pretty weird. And there are still painfully few CP violating processes that can be studied experimentally.  $\Rightarrow$  we need to pursue every chance we get

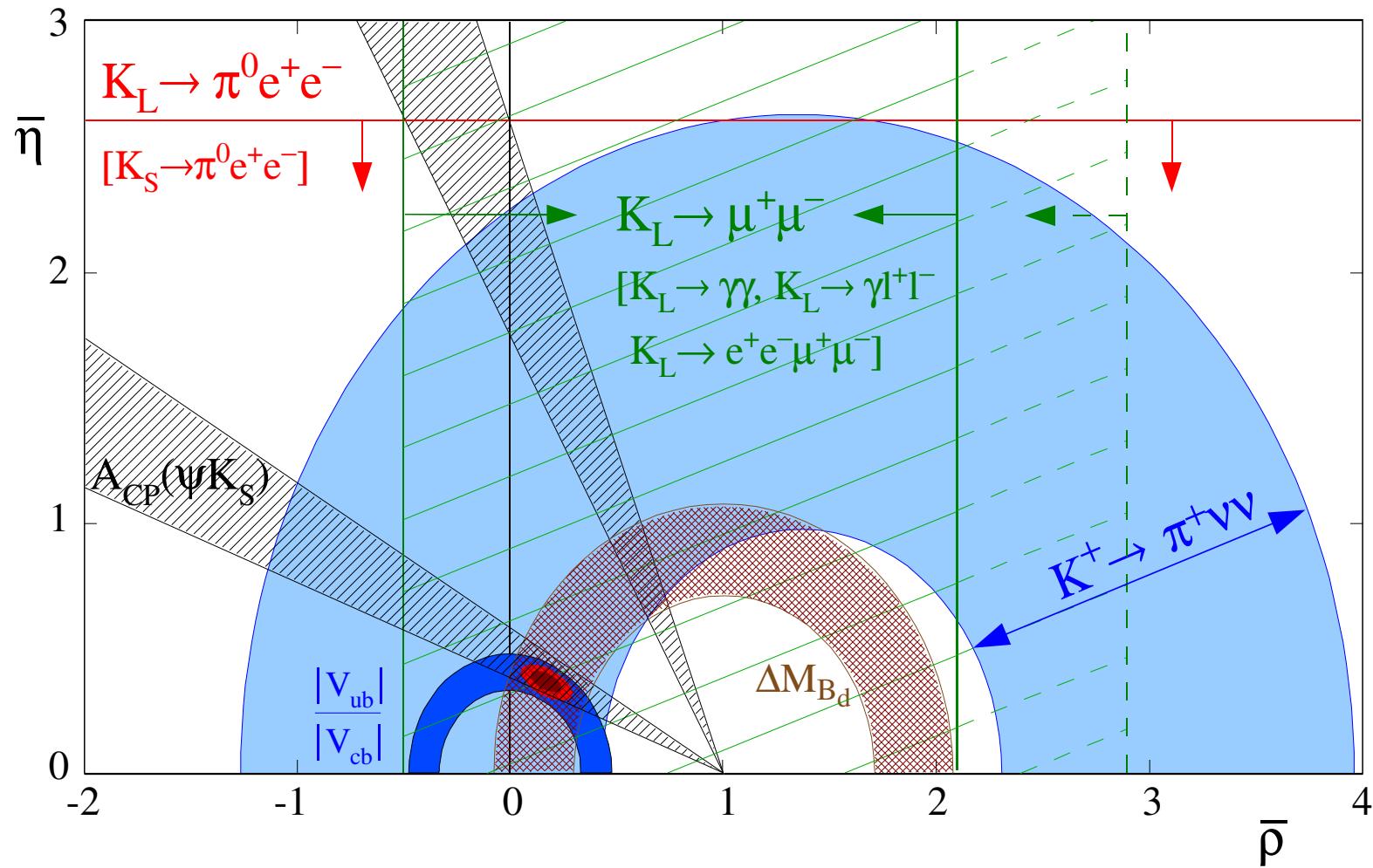
# FCNC Matrix<sup>a</sup>

Towards a model independent approach to the flavour problem:

Th. error $\lesssim 10\%$	decreasing SM contrib.		
	$b \rightarrow s (\sim \lambda^2)$	$b \rightarrow d (\sim \lambda^3)$	$s \rightarrow d (\sim \lambda^5)$
$\Delta F=2$ box	$\Delta M_d$ $A_{CP}(B_s \rightarrow \psi K)$	$\Delta M_s$ $A_{CP}(B_s \rightarrow \psi \phi)$	$\Delta M_K$ $\varepsilon_K$
	$B_d \rightarrow \pi K$ , $B_d \rightarrow \eta K$ , $A_{CP}(B_d \rightarrow \phi K)$ , ...	$B_d \rightarrow \pi \pi$ , $B_d \rightarrow \rho \pi$ , $A_{CP}(B_d \rightarrow \pi \pi)$ , ...	$\varepsilon' / \varepsilon$ , $A_{CP}(K \rightarrow 3\pi)$ , ...
	$B_d \rightarrow X_s \gamma$ $B_d \rightarrow \pi K$ , $A_{CP}(B_d \rightarrow \phi K)$ , ...	$B_d \rightarrow X_d \gamma$ $B_d \rightarrow \pi \pi$ , $A_{CP}(B_d \rightarrow \pi \pi)$ , ...	$K_L \rightarrow \pi^0 l^+ l^-$ , $\varepsilon' / \varepsilon$ , ...
	$B_d \rightarrow X_s l^+ l^-$ $B_d \rightarrow X_s \gamma$ $B_d \rightarrow \pi K$ , $B_s \rightarrow K K$ , ...	$B_d \rightarrow X_d l^+ l^-$ , $B_d \rightarrow X_d \gamma$ $B_d \rightarrow \pi \pi$ , $B_s \rightarrow \pi K$ , ...	$K_L \rightarrow \pi^0 l^+ l^-$ , $\varepsilon' / \varepsilon$ , ...
	$B_d \rightarrow X_s l^+ l^-$ $B_s \rightarrow \mu^+ \mu^-$ $B_d \rightarrow \pi K$ , $B_s \rightarrow K K$ , ...	$B_d \rightarrow X_d l^+ l^-$ , $B_d \rightarrow \mu^+ \mu^-$ $B_d \rightarrow \pi K$ , $B_s \rightarrow K K$ , ...	$K_L \rightarrow \pi^0 l^+ l^-$ , $K_L \rightarrow \pi^0 \nu \bar{\nu}$ $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ , $\varepsilon' / \varepsilon$ , ...
	$B_s \rightarrow \mu^+ \mu^-$	$B_d \rightarrow \mu^+ \mu^-$	$K_{L,S} \rightarrow \mu^+ \mu^-$

= exp. error  $\lesssim 10\%$ 
 = exp. error  $\sim 30-50\%$

# CKM constraints from kaon decays<sup>a</sup>



Still room for new effects in the  $sd$  and/or  $\Delta F = 1$  sectors...

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<sup>a</sup>Isidori, Unterdorfer: JHEP 0401 (2004) 009

# $K_L \rightarrow \pi^0 \nu \bar{\nu}$ in the Std. Model

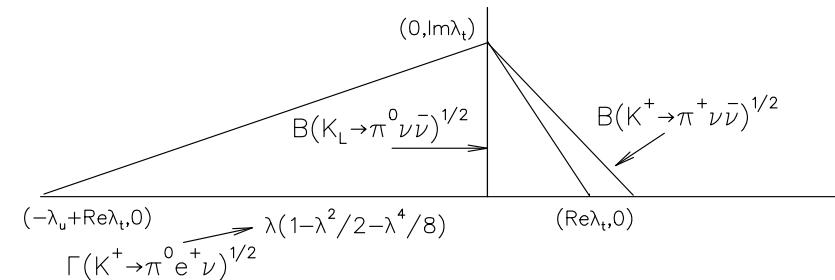
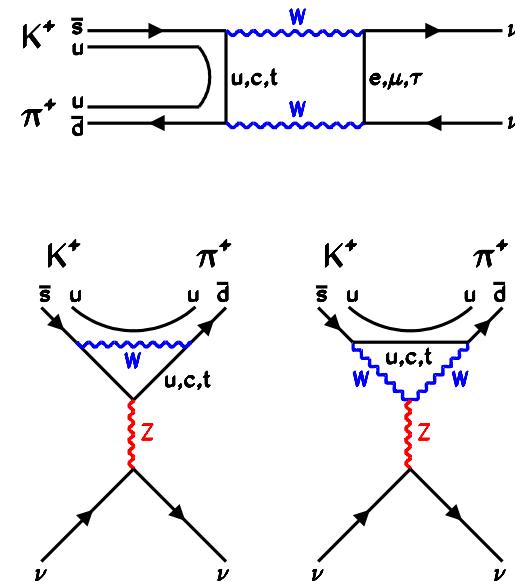
Similar considerations to  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  with some important differences

- Almost completely CP violating. CP conserving contribution<sup>a</sup>  $< 10^{-4}$
- Top quark **completely** dominates in loops
- Even cleaner theoretically:  $\delta(\text{BR}) \sim 2\%$
- Std. Model expectation:<sup>b</sup>  $(0.30 \pm 0.06) \times 10^{-10}$
- Yields height (area) of unitarity triangle

Model-independent bound:<sup>c</sup>

$$\frac{BR(K_L \rightarrow \pi^0 \nu \bar{\nu})}{BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})} < \frac{\tau_L}{\tau_+} \times \frac{1}{r_{is}} \sim 4.4$$

$$\text{or } BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 1.4 \times 10^{-9}$$



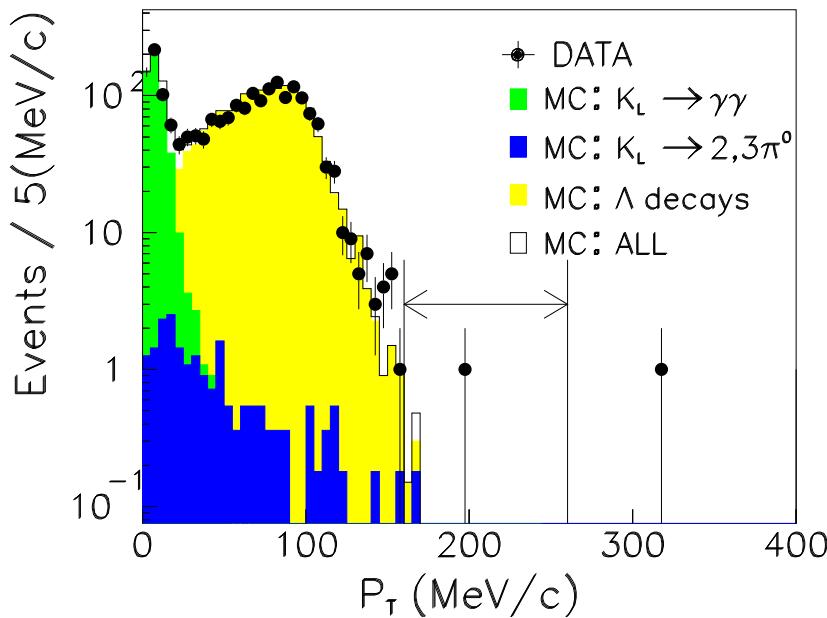
<sup>a</sup>Buchalla and Isidori, PL B440 (1998) 170

<sup>b</sup>Buras *et al*, hep-ph/0405132

<sup>c</sup>Grossman, Nir, PL B398 (1997) 163

# $K_L \rightarrow \pi^0 \nu \bar{\nu}$ experimental history

- First experimental limit actually came from Princeton experiment<sup>a</sup> although they did not know it at the time!
- Analysis by L. Littenberg:<sup>b</sup>  $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 7.6 \times 10^{-3}$  (90% CL)
- Best experimental limit so far comes from KTeV<sup>c</sup> utilizing Dalitz decay of  $\pi^0$ :  
 $\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 5.9 \times 10^{-7}$  (90% CL)
- Future experiments will utilize the  $\pi^0 \rightarrow \gamma\gamma$  mode



KTeV one day test run in 1997.

- $K_L \rightarrow \pi^0 \nu \bar{\nu}, \pi^0 \rightarrow \gamma\gamma$
- “Pencil” beam
- Background consistent with neutron interactions
- $\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 1.6 \times 10^{-6}$  (90% CL)<sup>d</sup>

<sup>a</sup>Cronin et al., PRL 18 (1967) 25

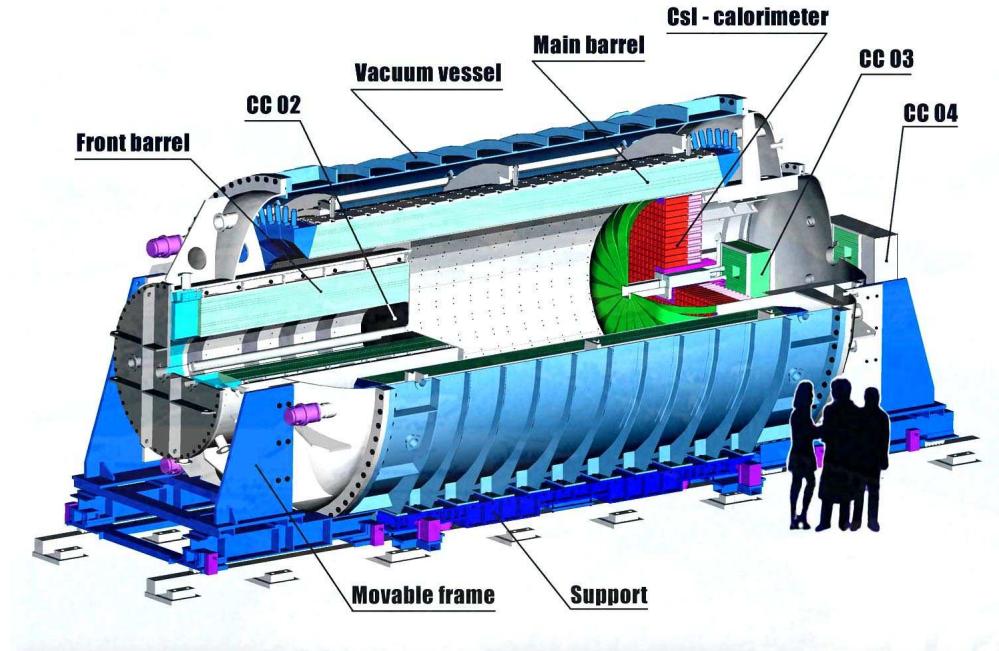
<sup>b</sup>PRD 39 (1989) 3322

<sup>c</sup>PR D61 (2000) 072006

<sup>d</sup>PL B447 (1999) 240

# KEK E391a

KEK E391a is the first dedicated experiment to search for  $K_L \rightarrow \pi^0 \nu \bar{\nu}$ .

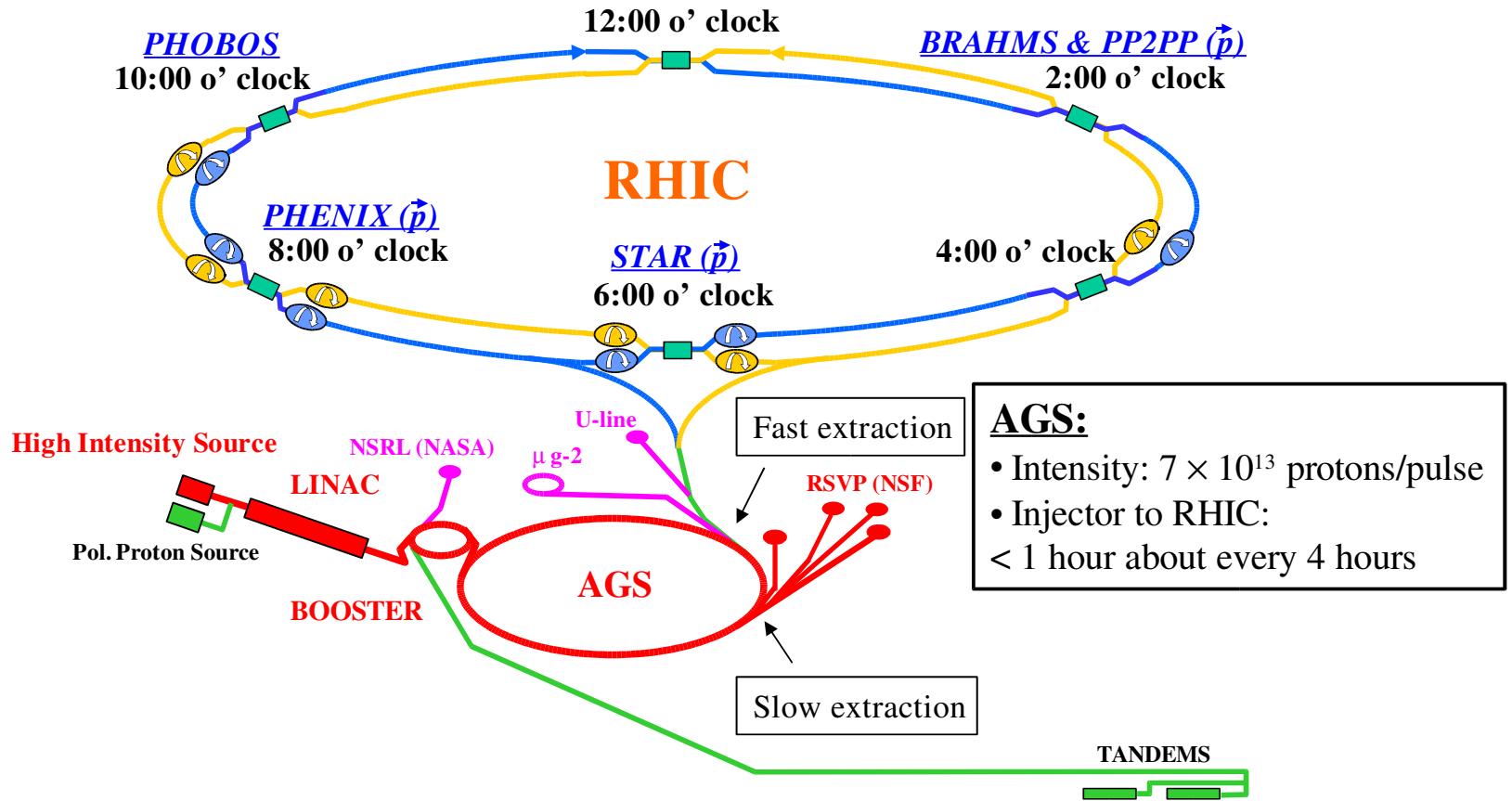


- “Pencil” beam, high acceptance.
- Ran mid-February 2004 through June. Could reach SES  $\sim 4 \times 10^{-10}$  (below Grossman-Nir bound) assuming very loose photon veto cuts. Proposed to run again in 2005.
- Prototype for future experiments at e.g. JPARC. Photon veto performance will be very interesting for e.g. KOPIO.

# HEP@BNL in the RHIC era



# AGS/RHIC Accelerator Complex



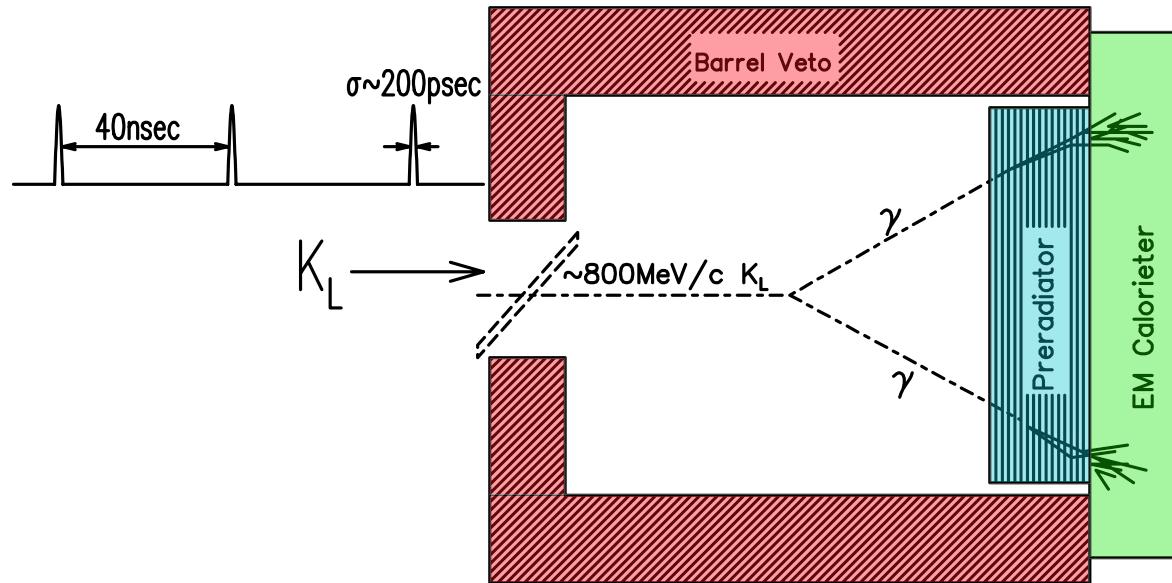
# KOPIO Collaboration

- Arizona State University
- UBC
- BNL
- IHEP
- INR
- KEK
- Kyoto University
- University of New Mexico
- INFN Perugia
- Stony Brook
- TRIUMF
- Virginia Tech
- Yale
- University of Zurich

# KOPIO concept

“Yesterday’s signal is today’s background”

- $\mathcal{B}(K_L \rightarrow \pi^0 \pi^0) \sim 10^{-3}$  vs  $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \sim 3 \times 10^{-11}$
- $\pi^0$  veto:  $(10^{-4})^2 = 10^8$  rejection
- Extra handle comes from kinematics

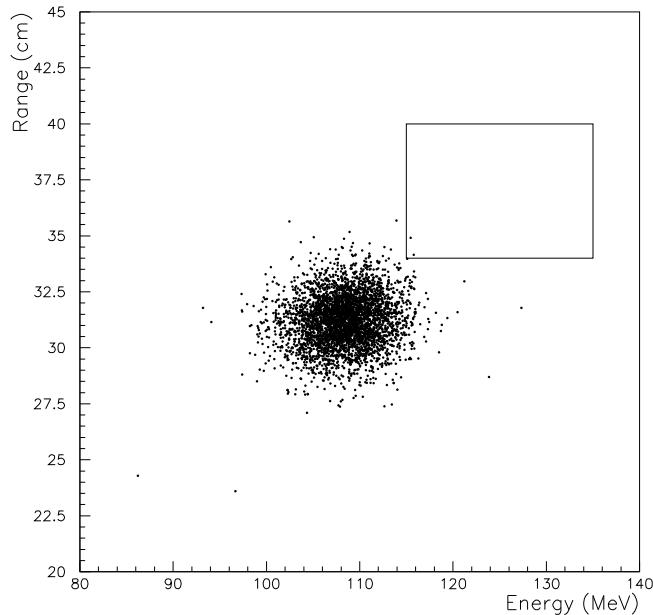


- Low energy “microbunched” beam.  $\sim 45^\circ$  production angle. TOF to get  $K_L$  momentum
- Photon angle measurement to get  $K_L$  decay vertex and  $\pi^0$  direction. Additional constraint from flat beam profile.

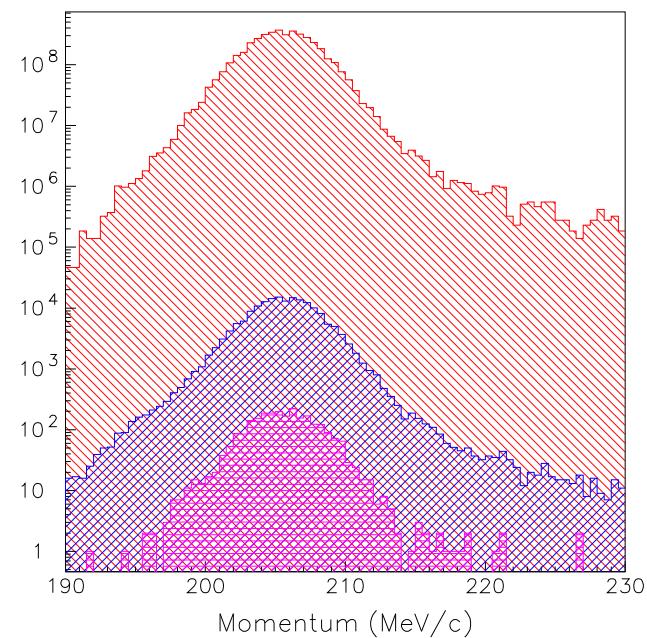
# Lessons from E787

- E787 was able to reliably estimate backgrounds that came in at the  $10^{-11} - 10^{-12}$  level with a dual cut technique
- Example:  $K^+ \rightarrow \pi^+\pi^0$  background to  $K^+ \rightarrow \pi^+\nu\bar{\nu}$

Events tagged with presence of  $\gamma$ s



Events tagged by  $K_{\pi 2}$  kinematics

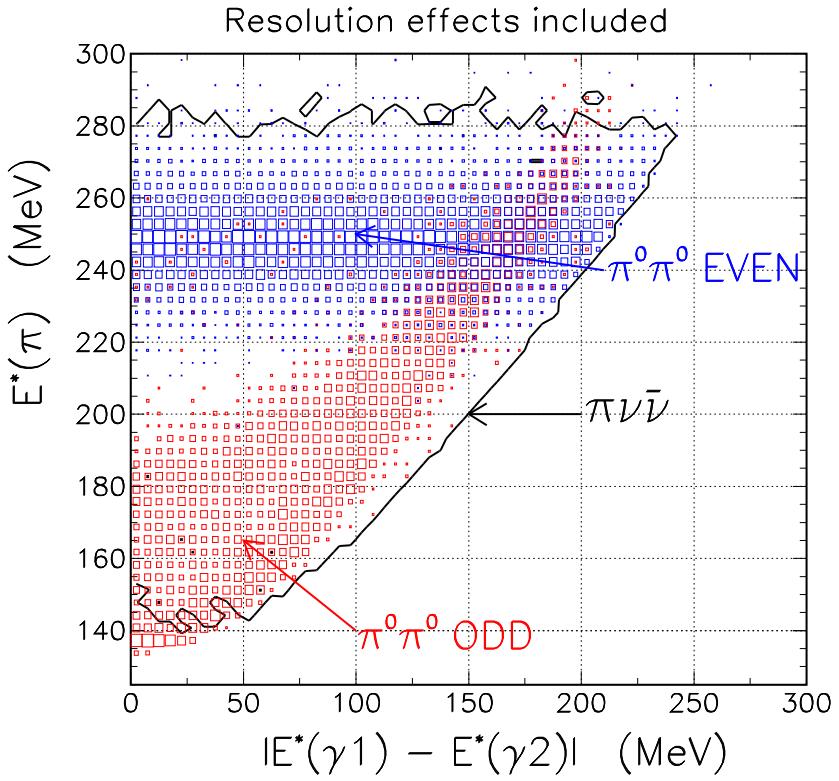
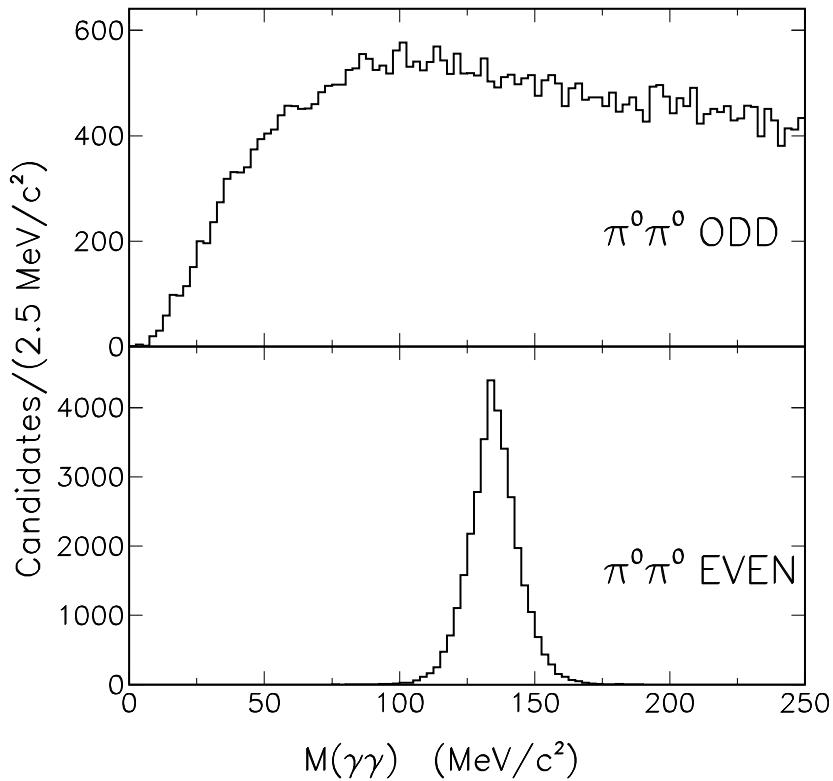


$$N_{bkg} = \frac{N}{R_{PV} - 1}$$

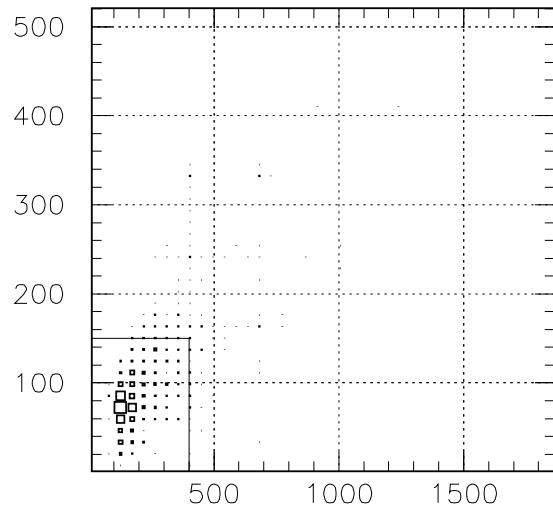
- Prediction (and confirmation) of background levels “outside the box”
- S/N characterization inside the box

# Background suppression: $K_L \rightarrow \pi^0\pi^0$ kinematics

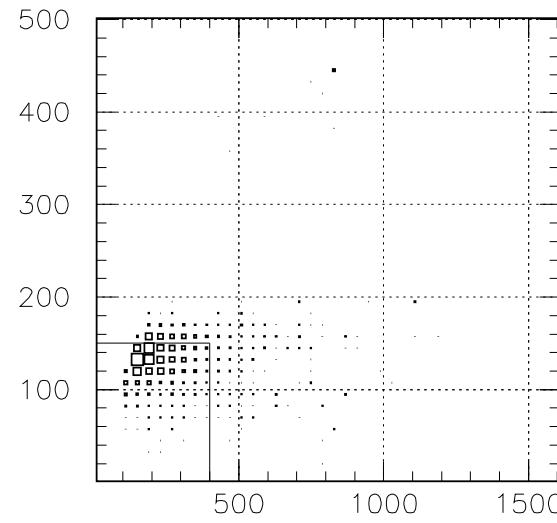
$K_L \rightarrow \pi^0\pi^0$  with 2 missing photons is the dominant background:



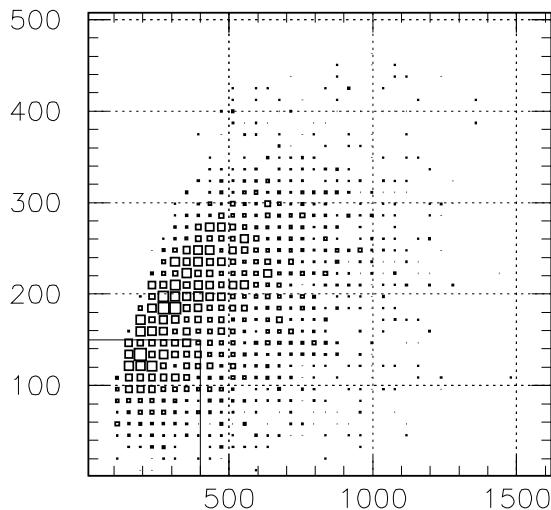
# Background suppression: $K_L \rightarrow \pi^0\pi^0$



Miss-Mass vs. Miss-E (Kpi2-odd)



Miss-Mass vs. Miss-E (Kpi2-even)



Miss-Mass vs. Miss-E (pinn)

- ➊ Missing energy cut effective in removing events where low- $E$   $\gamma$  lost  $\Rightarrow$  improves photon veto rejection
- ➋ For asymmetric  $\pi^0$  decays, cut on missing mass is effective.

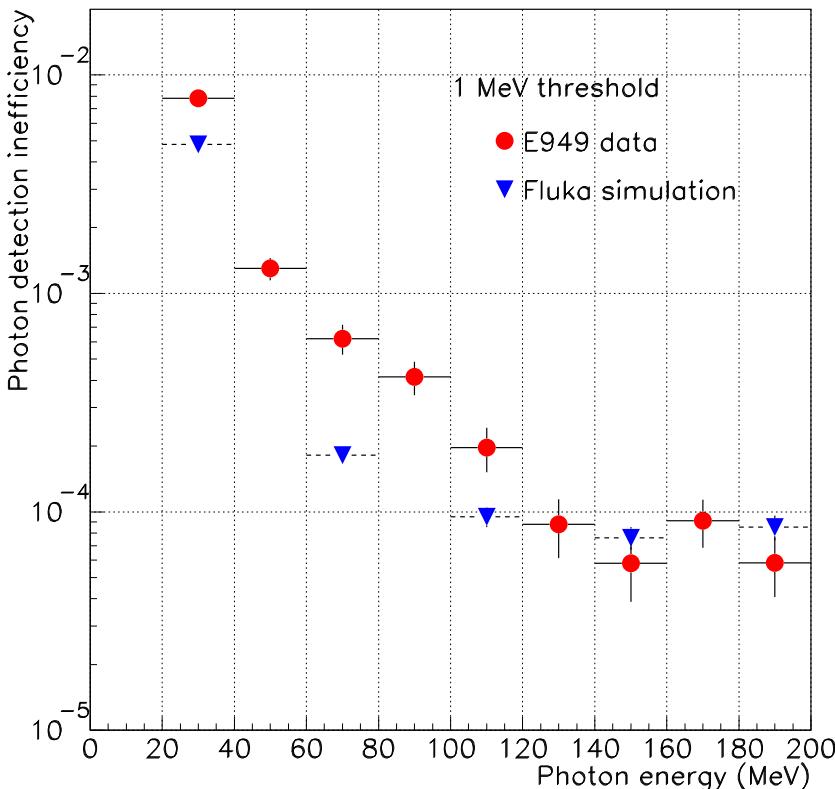
$$M_{miss} \propto \sqrt{E_{miss\gamma 1} \cdot E_{miss\gamma 2}}$$

# Photon veto

- $\pi^0$  detection inefficiency of  $10^{-8}$  is required.
- E787 obtained  $\pi^0$  detection inefficiency  $\sim 10^6$ , roughly understood as

$$\begin{aligned}\bar{\epsilon}_\gamma &\sim 10^{-4} \quad E_\gamma = [100, 220] \text{ MeV} \\ &\sim 10^{-2} \quad E_\gamma = [20, 100] \text{ MeV}\end{aligned}$$

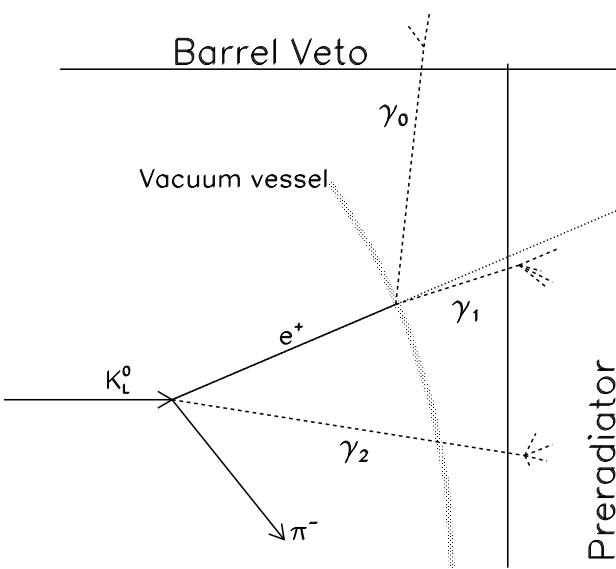
E949  $K^+ \rightarrow \pi^+ \pi^0$  data:



## KOPIO strategy

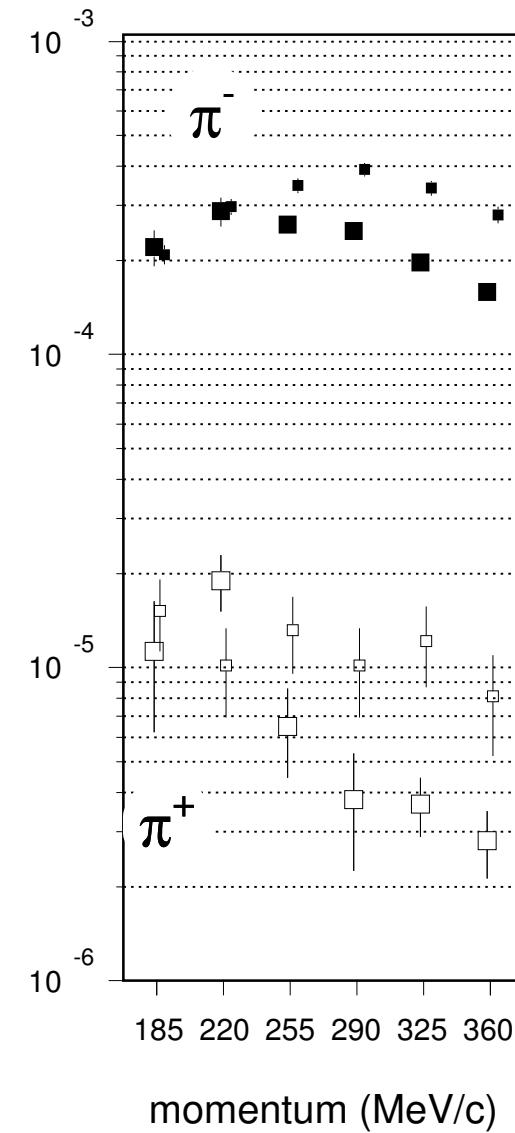
- Thinner Pb thickness per layer than E787/E949. More radiation lengths.
- Suppress low energy  $\gamma$  with cuts on missing mass/energy  $\Rightarrow \bar{\epsilon}_{\pi^0} \sim (10^{-4})(10^{-4}) = 10^{-8}$

# Charged particle veto



Inefficiency measurements at PSI  
(200 keV threshold)

particle	$e^-$	$e^+$	$\pi^-$	$\pi^+$
ineff	$< 10^{-5}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-5}$

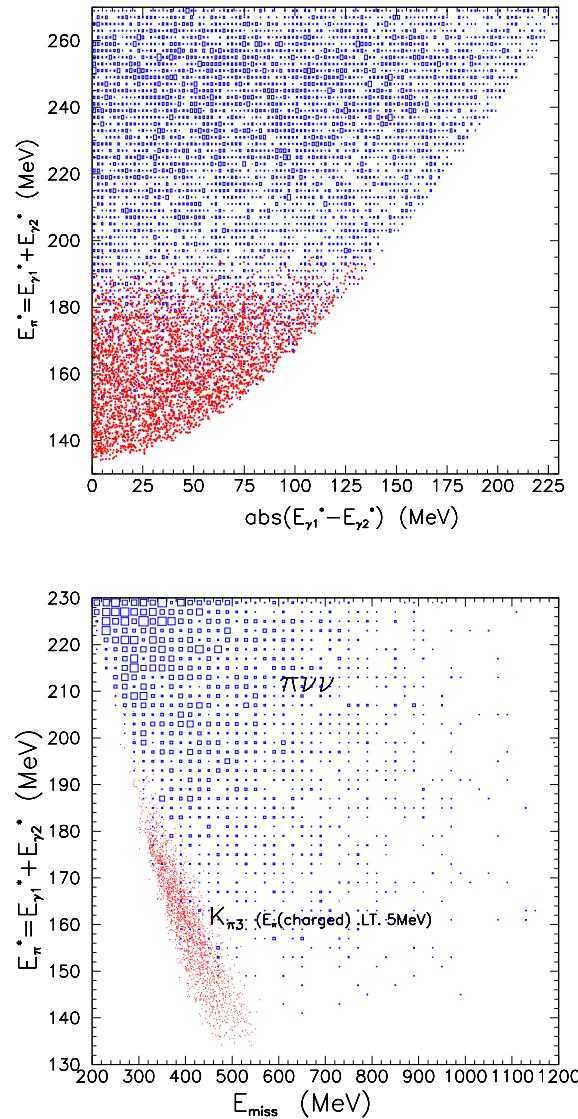
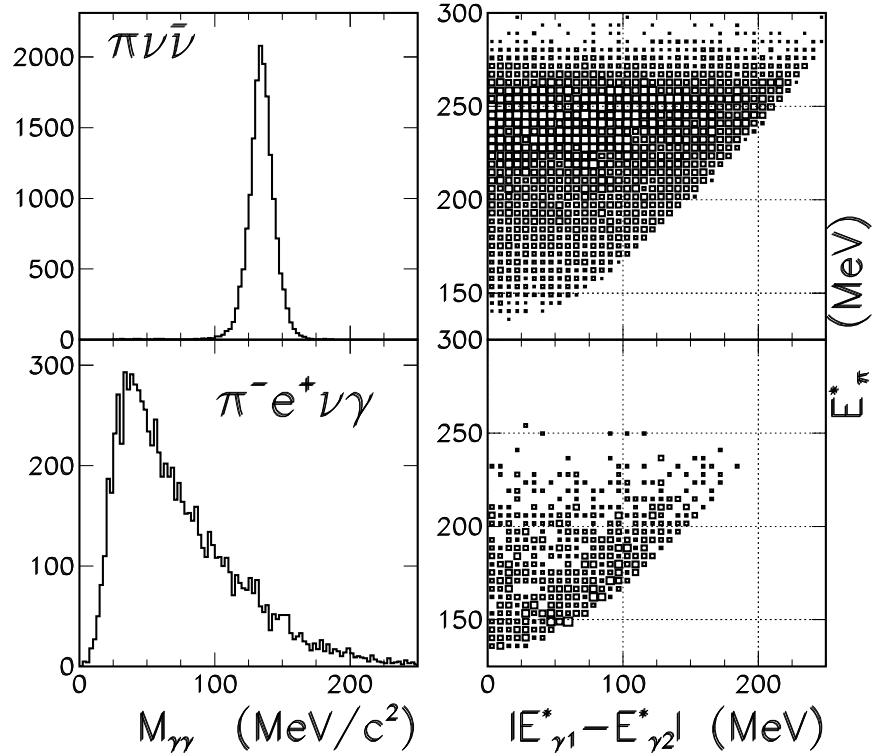


- To reach  $10^{-4}$  for  $\pi^-$ , detection threshold must be  $\sim 75\text{keV}$  (0.3mm of scintillator)
- Tests with scintillator sheets with direct PMT readout reach threshold  $\sim 10\text{keV}$
- Dead material in front of veto system must be below  $20\text{mg/cm}^2$

# Kinematic handles on charged modes

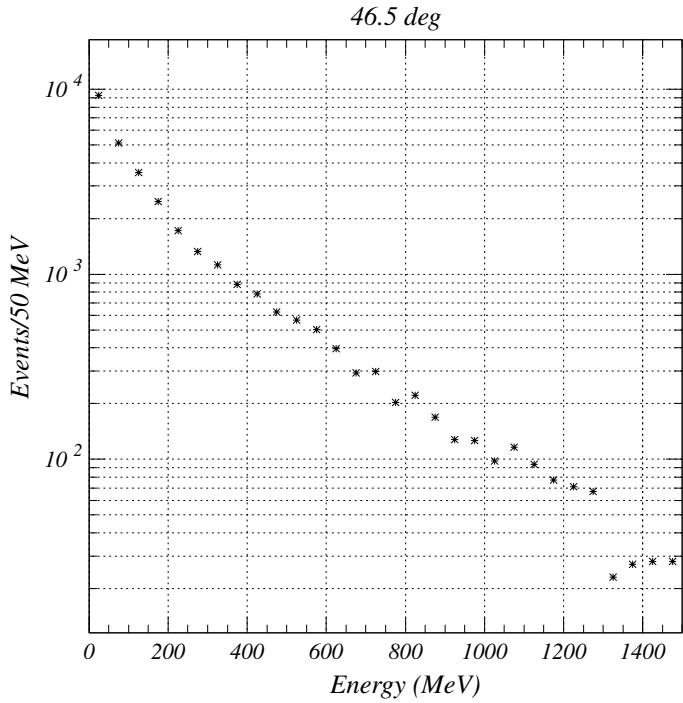
$K_L \rightarrow \pi^+ \pi^- \pi^0:$

$K_L \rightarrow \pi^\pm e^\mp \nu\gamma:$

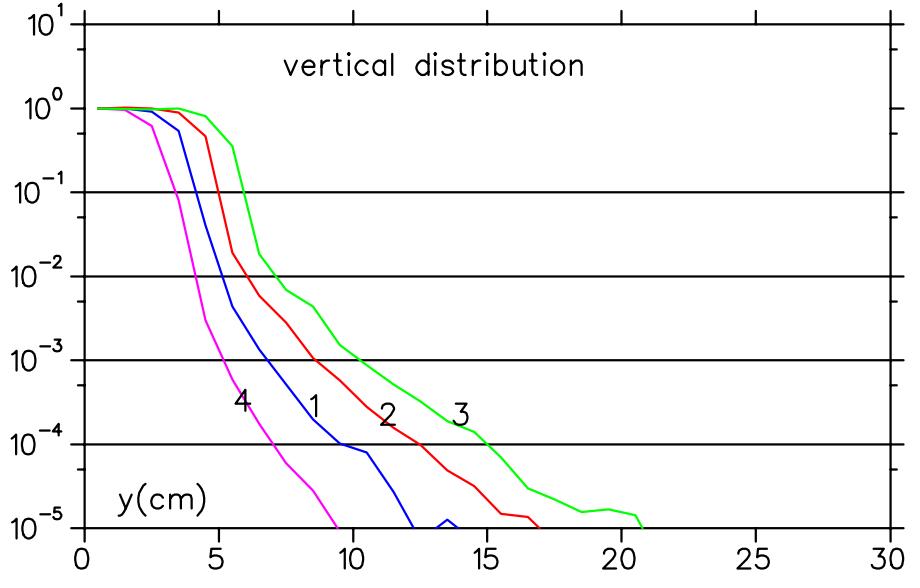
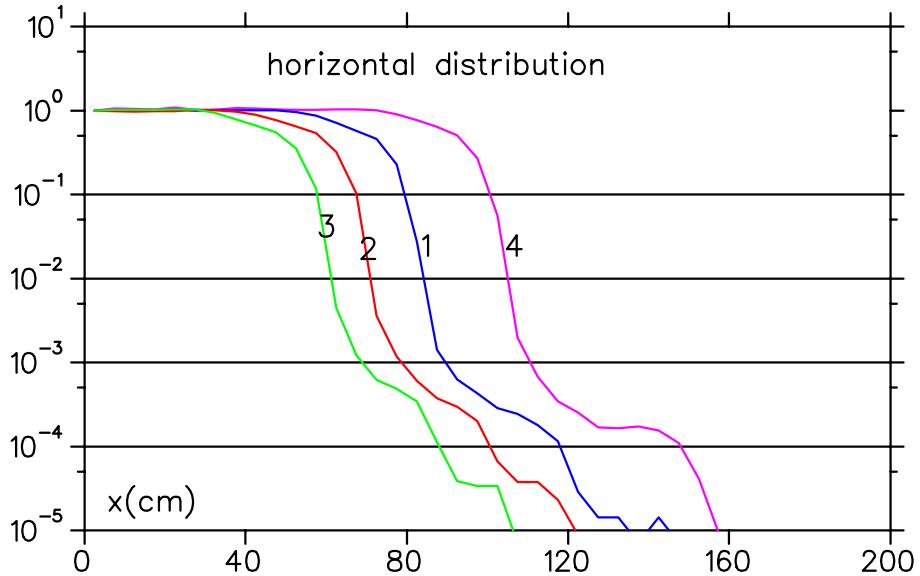


# Neutrons

## Neutron energy



## Neutron halo



$n/K_L \sim 300$ , but

- $\pi^0$  production threshold:  $\sim 260$  MeV
- Vacuum:  $\sim 10^{-7}$
- Tight beam collimation
- Good  $\pi^0$  vertex resolution

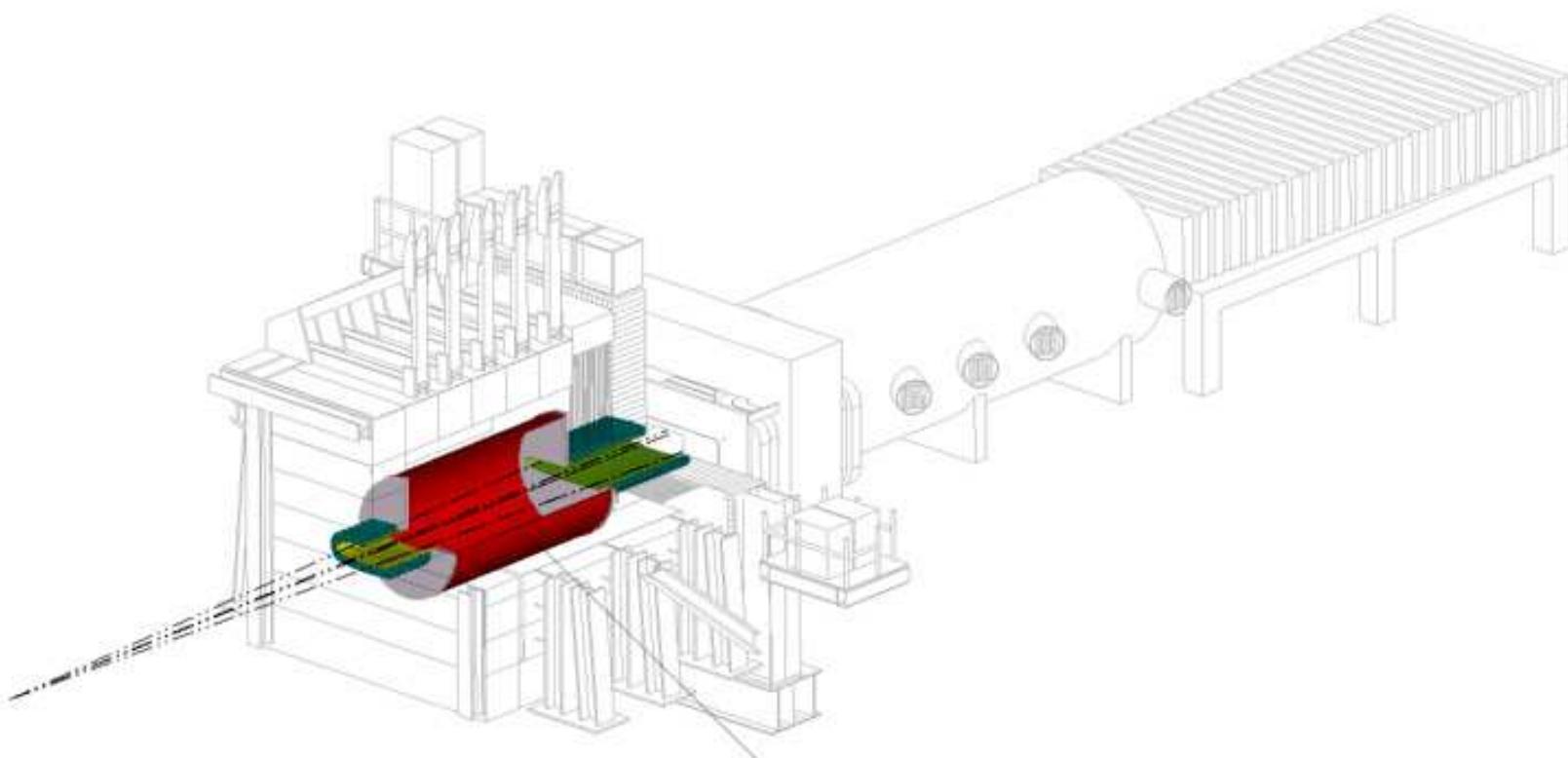
make neutron/hyperon bkg negligible

# Background summary

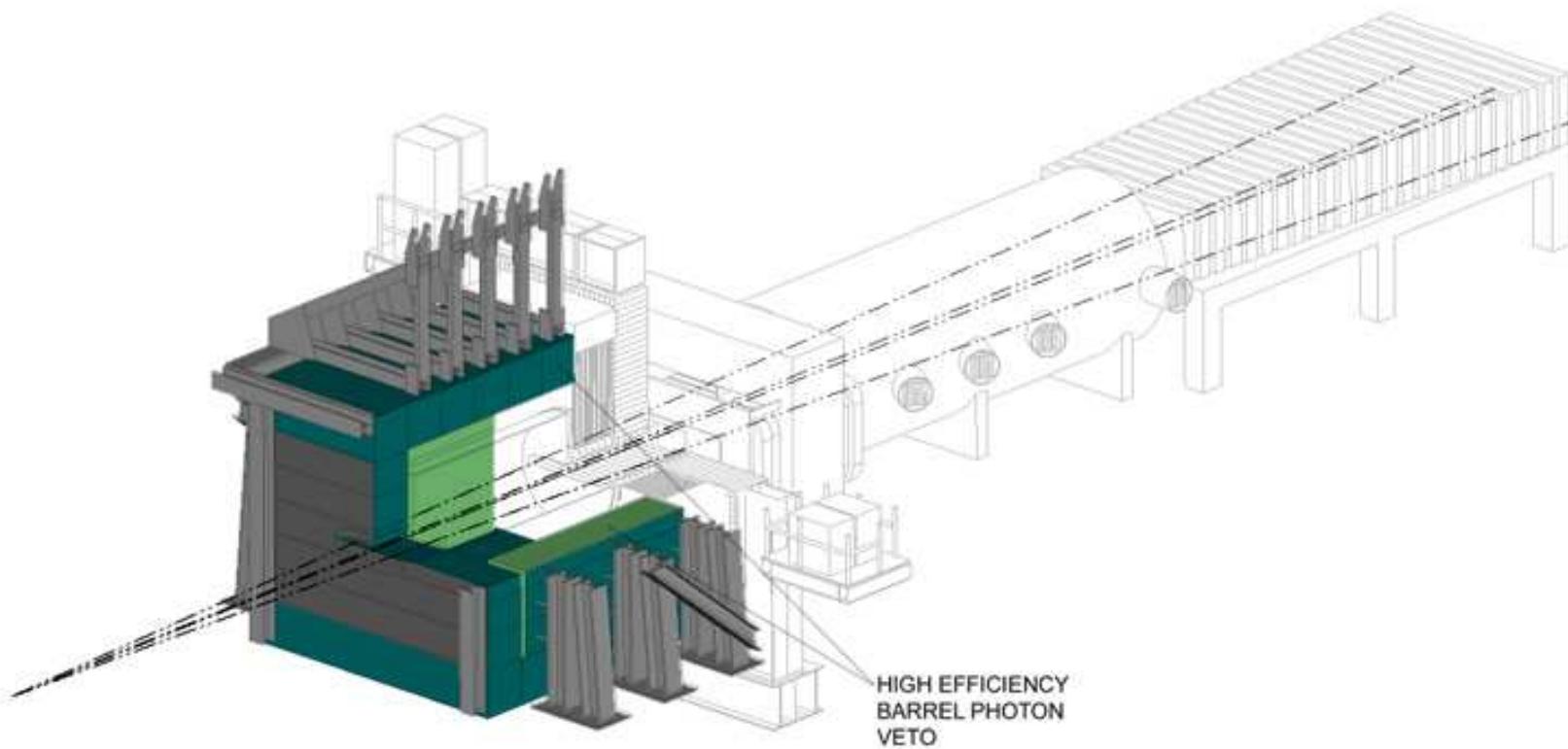
Modes	Main source	Events
$K_L \rightarrow \pi^0 \nu \bar{\nu}$ ( $B = 3 \times 10^{-11}$ )		49
$\pi^0 \pi^0, \pi^0 \pi^0 \pi^0, \pi^0 \gamma \gamma$	$\pi^0 \pi^0$	14
$\pi^\pm l^\mp \nu \gamma, \pi^\pm l^\mp \nu \pi^0, \pi^+ \pi^- \gamma$	$\pi^- e^+ \nu \gamma$	5
$\pi^+ \pi^- \pi^0$		3
Other	Accidentals	1
$\gamma \gamma$		
$\pi^\pm e^\mp \nu, \pi^\pm \mu^\mp \nu, \pi^+ \pi^-$		
$\Lambda \rightarrow \pi^0 n, \Sigma^+ \rightarrow \pi^0 p, K^\pm \rightarrow \pi^\pm \pi^0$		
Interactions: n, $K_L$ , $\gamma$		
Accidentals: n, $K_L$ , $\gamma$		
Total background		23

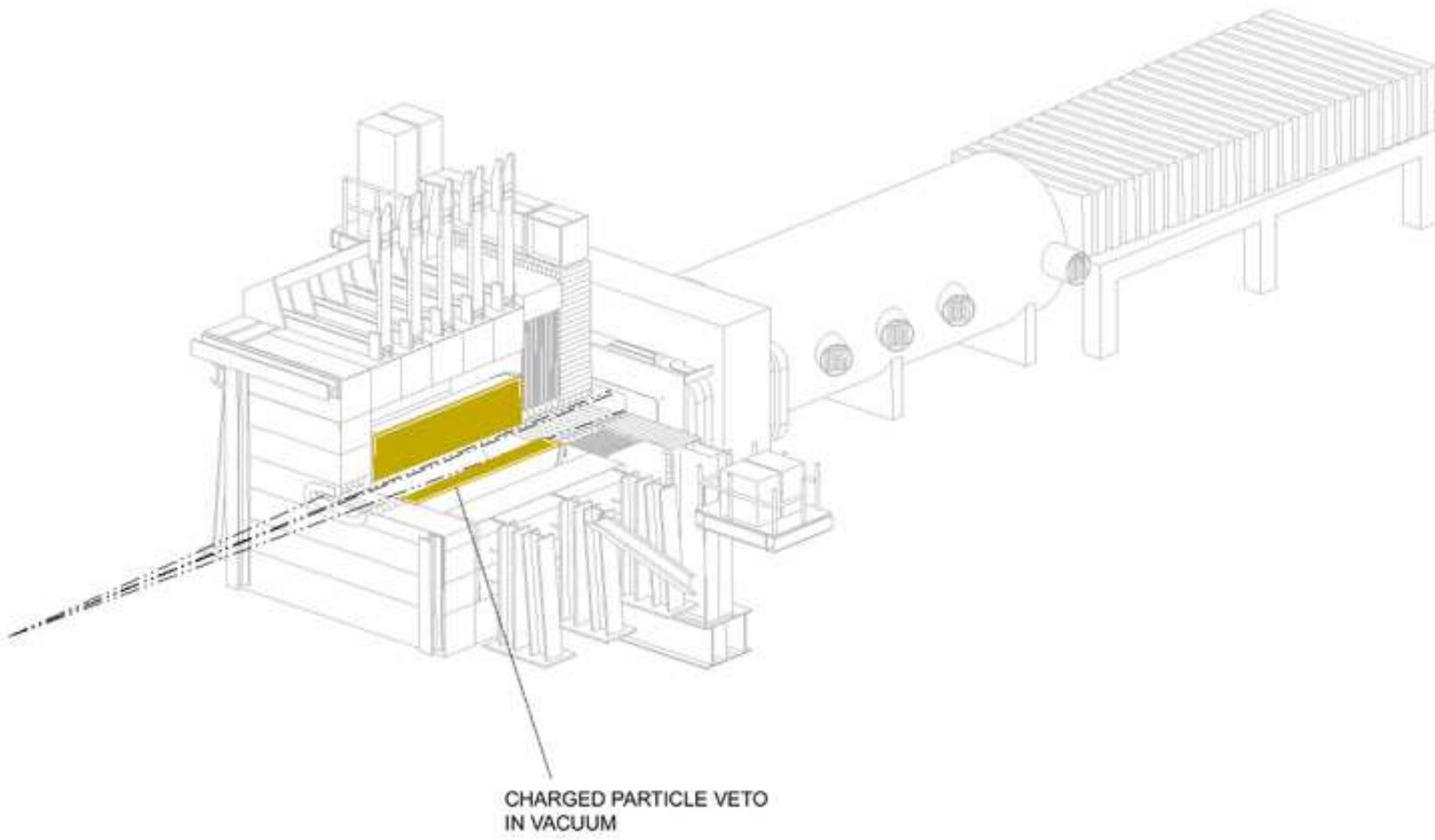
- Acceptance:  $9 \times 10^{-3}$

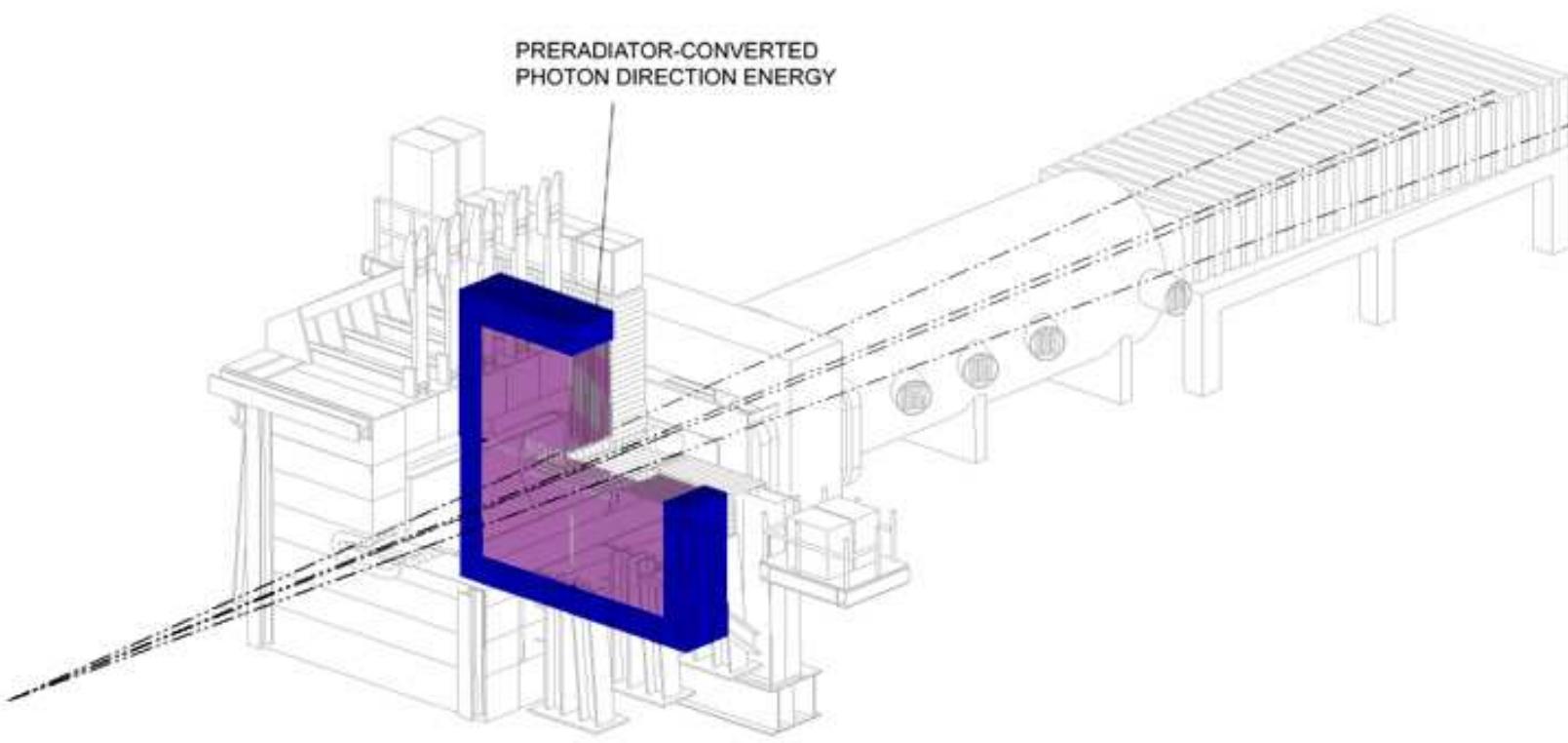
- 9600 hours

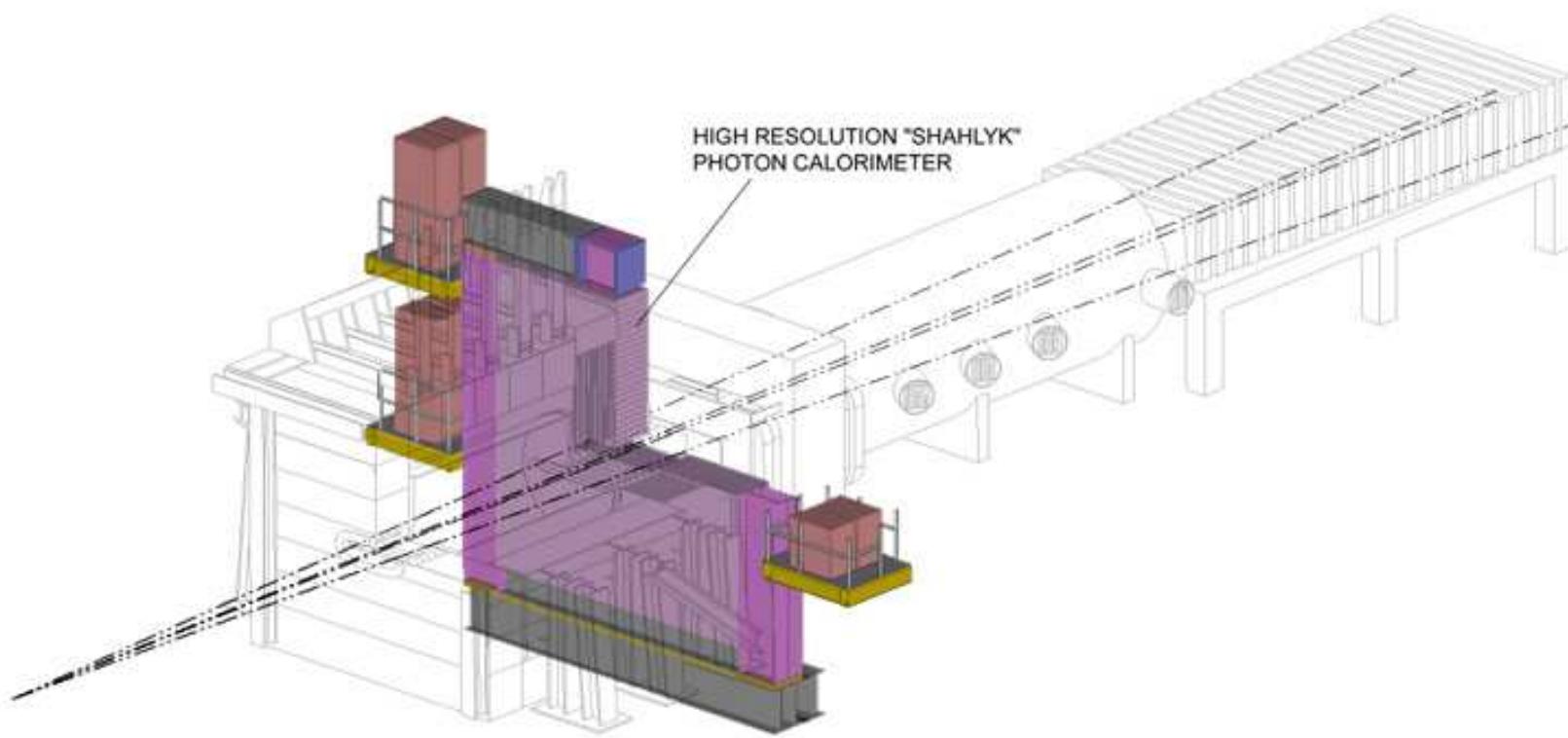


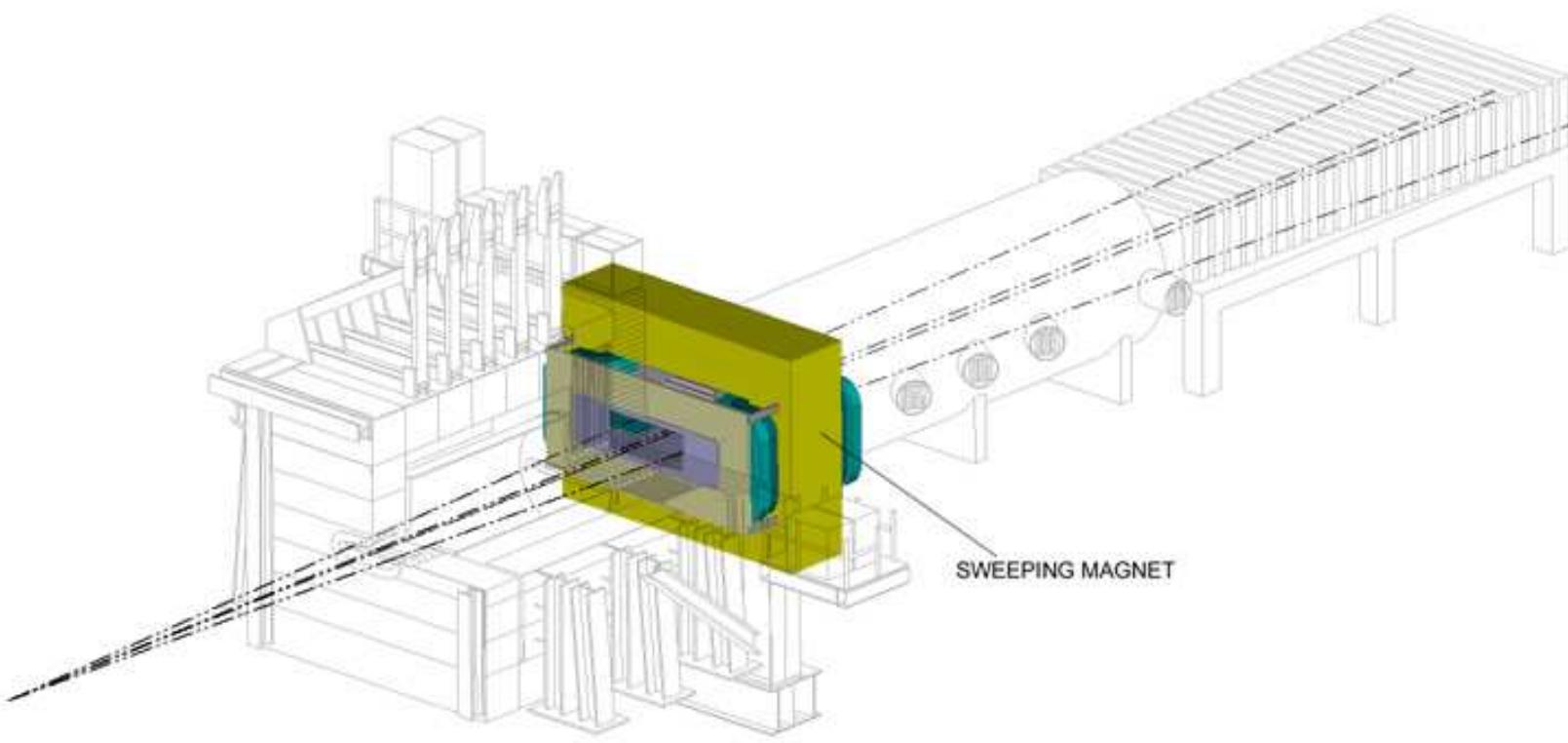
THIN WALLED  
HIGH VACUUM VESSEL  
IN DECAY REGION

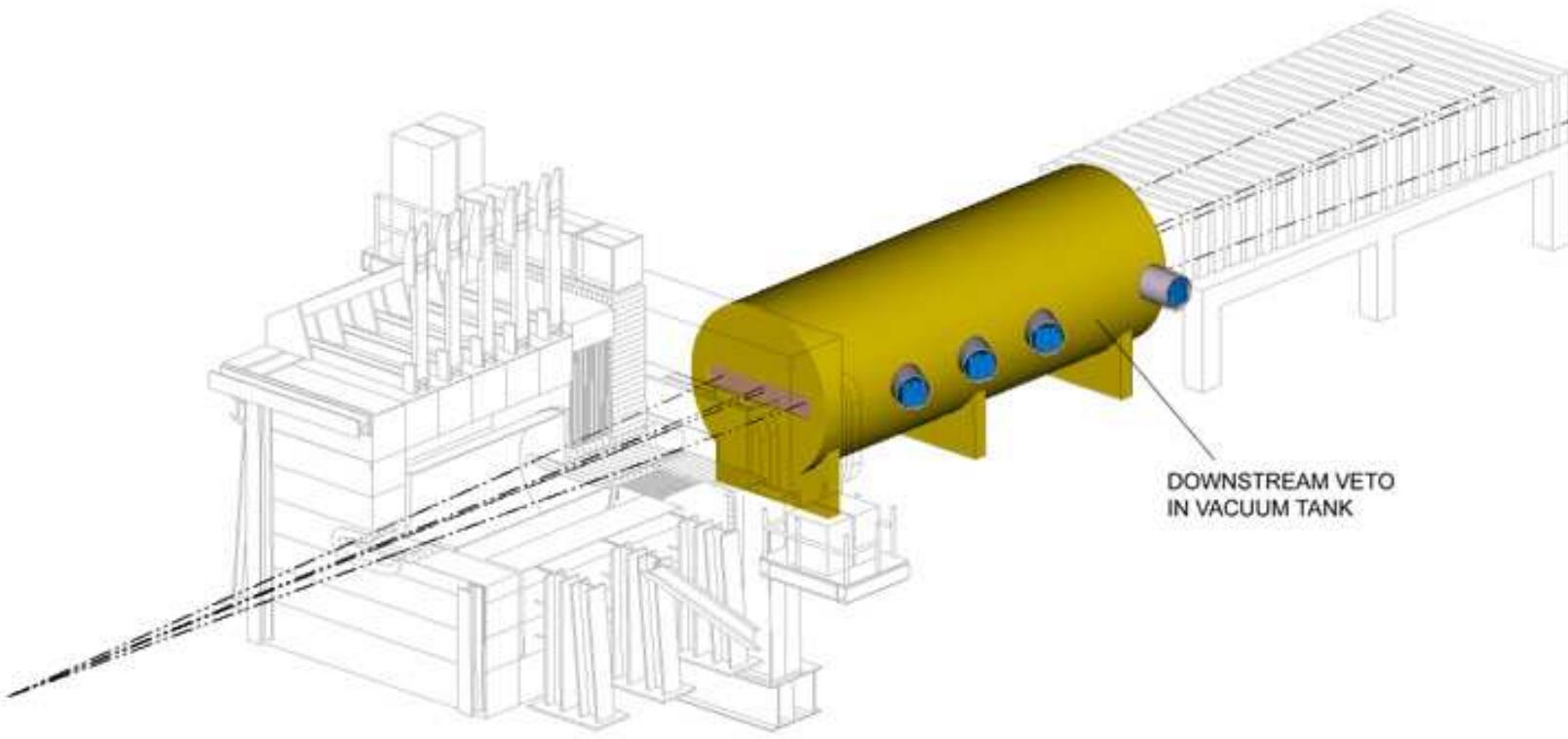


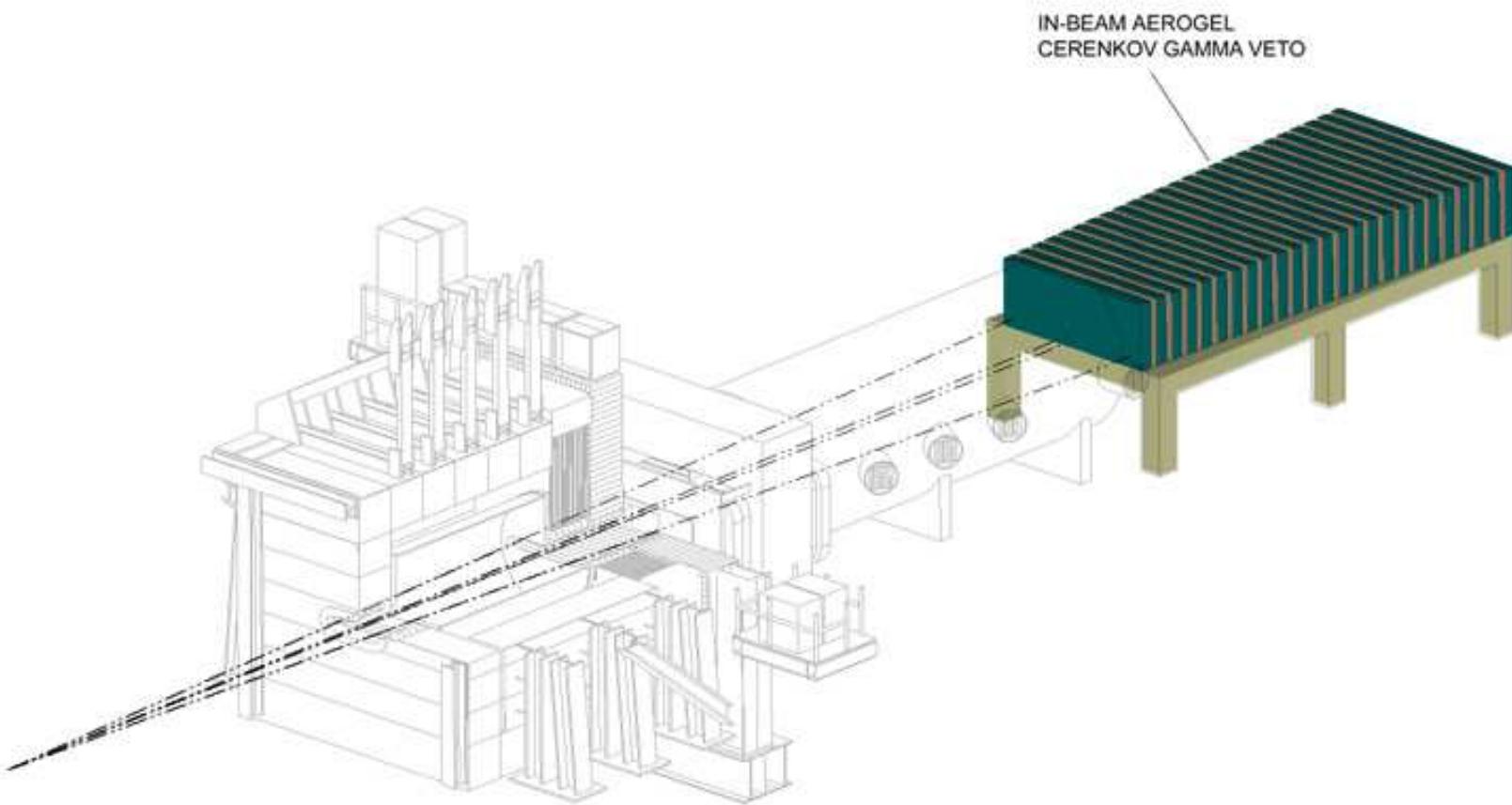












# Beam

- Proton beam

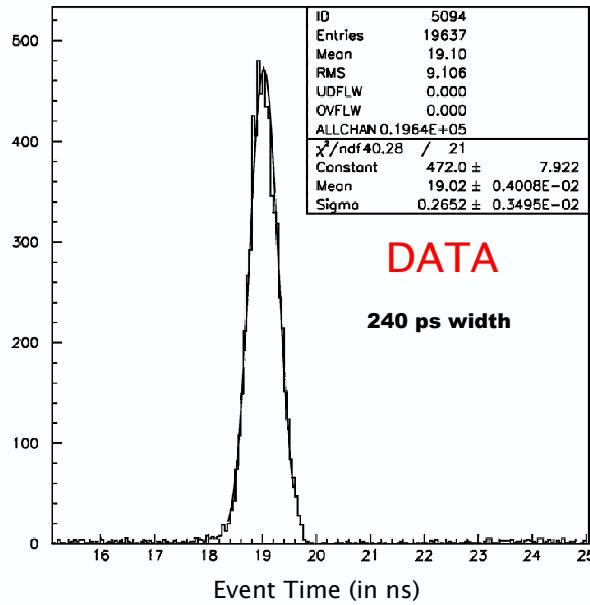
- $100 \times 10^{12}$  protons per 2.7 sec spill; 5 sec cycle time; needs AGS injection energy upgrade
- $p \sim 25 \text{ GeV}/c$
- Slow extraction with micro-bunching ( $\sigma = 200\text{ps}$  every 40 ns)
- Interbunch extinction  $\sim 10^{-3}$

- $K_L$  beam

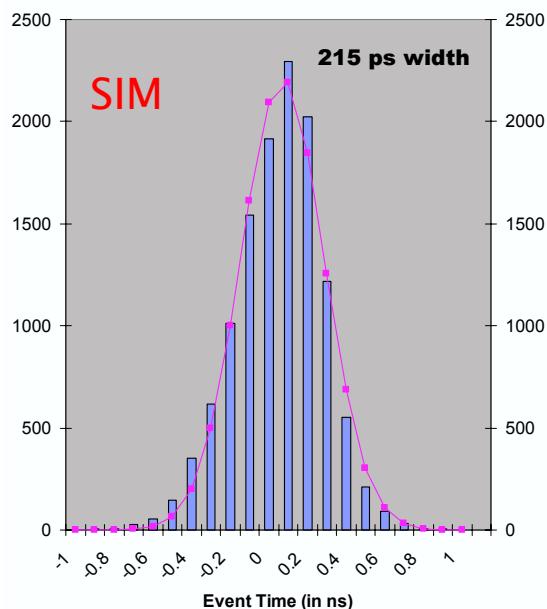
- $\sim 45^\circ$  production angle
- Low energy “pancake” beam:  $[0.5, 1.5] \text{ GeV}$ ,  $5mr \times 100mr$
- $\sim 10^8 K_L$  per spill, 12% decay
- $\sim 3 \times 10^{10}$  neutrons per spill
- Vacuum  $\sim 10^{-7} \text{ Torr}$

# Microbunching: bunch width

93 MHz data

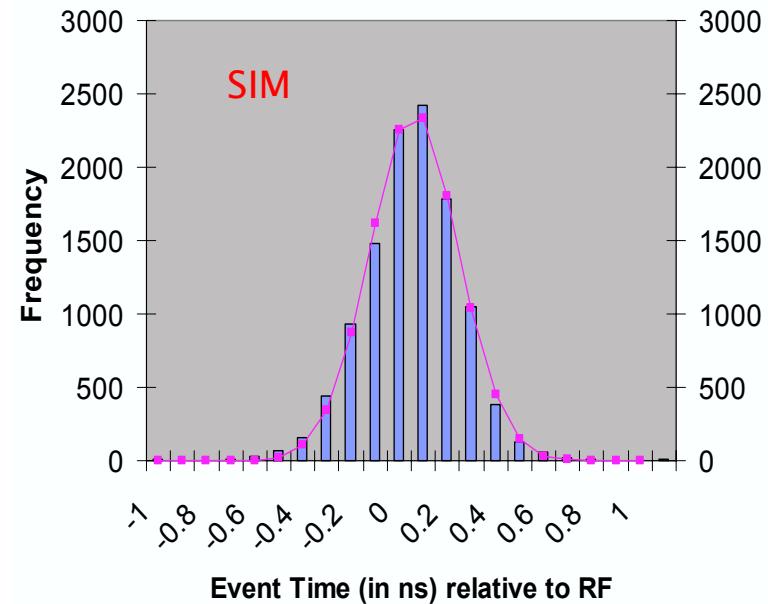


93 MHz simulation



KOPIO Simulation (185ps width)

KOPIO RF (25/100 MHz @ 150 kV)

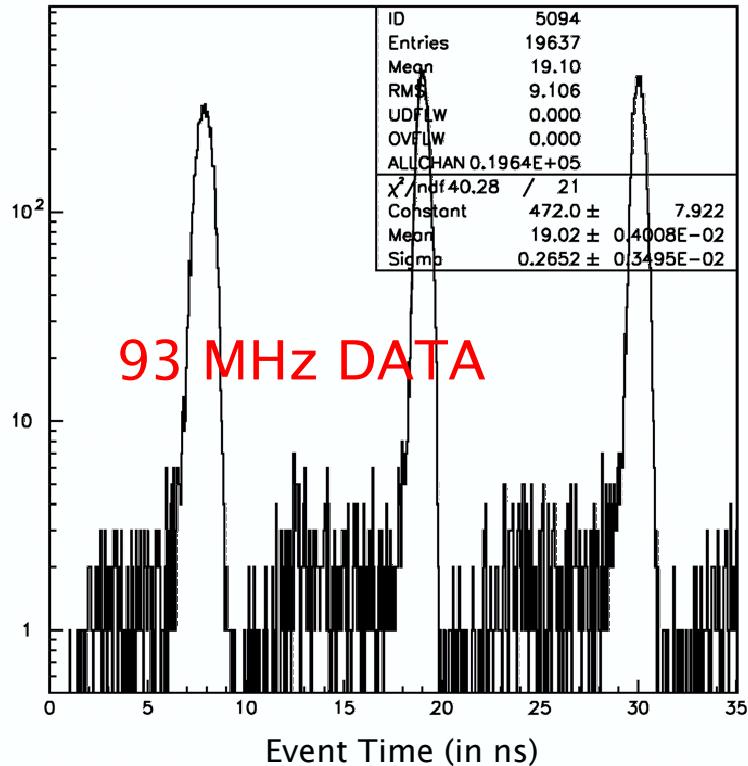


- Beam tests of microbunching have been done with a 93MHz RF cavity.

- KOPIO: 25 MHz cavity to get 40ns microbunch spacing and 100 MHz cavity to get the microbunch width

# Microbunching: interbunch extinction

~0.015 between bunches

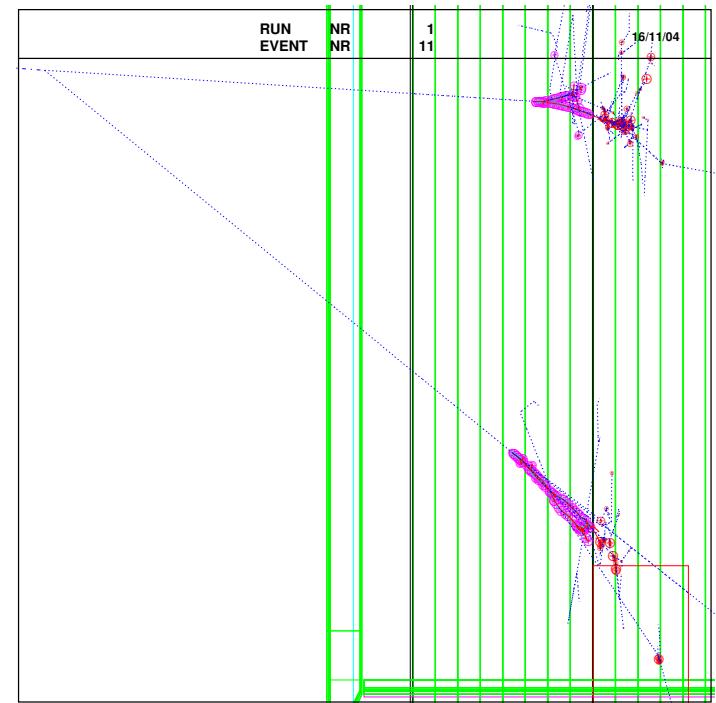
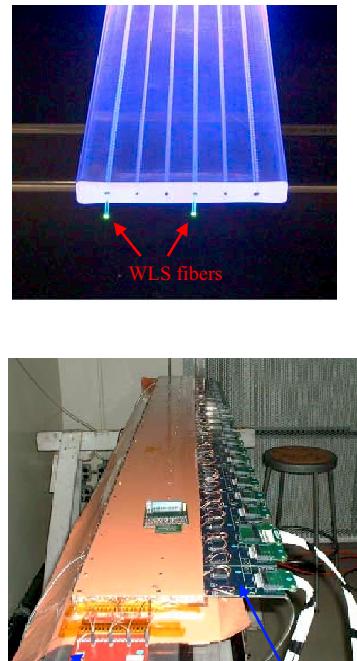
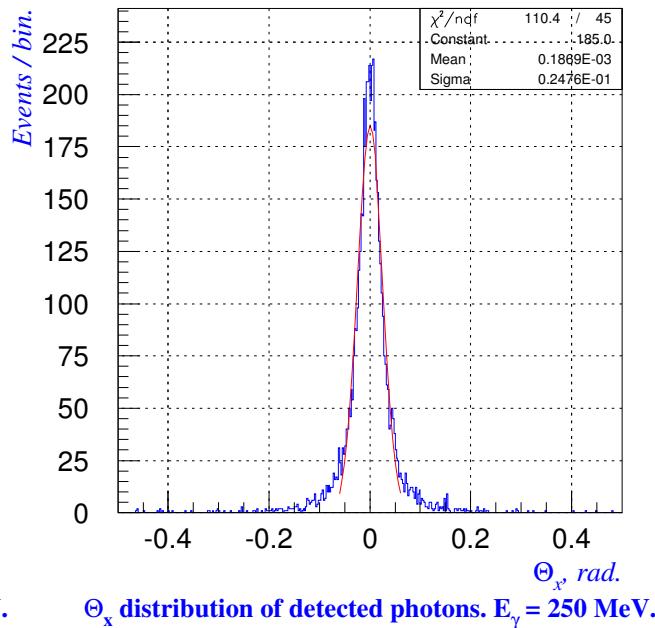


- Extinction of  $\sim 10^{-3}$  desired
- Need to control power supply ripple
- New test beam run completed this summer:
  - Improved systematics ( $\bar{p}$  beam)
  - Bunch width/extinction measured in a matrix of RF frequency, RF voltage and  $\frac{\Delta p}{p}$
  - Offline data analysis and comparisons to 4D simulation in progress

# Preradiator

- Track  $\gamma \rightarrow e^+e^-$  early in the shower.  $\sigma_\theta \sim 25mr$  needed.
- $\sim 0.03X_0$  per layer.  $2X_0$  in total.
- 200000 electronics channels
- In progress: full scale prototypes, HV and readout electronics, scintillator production, full mechanical design

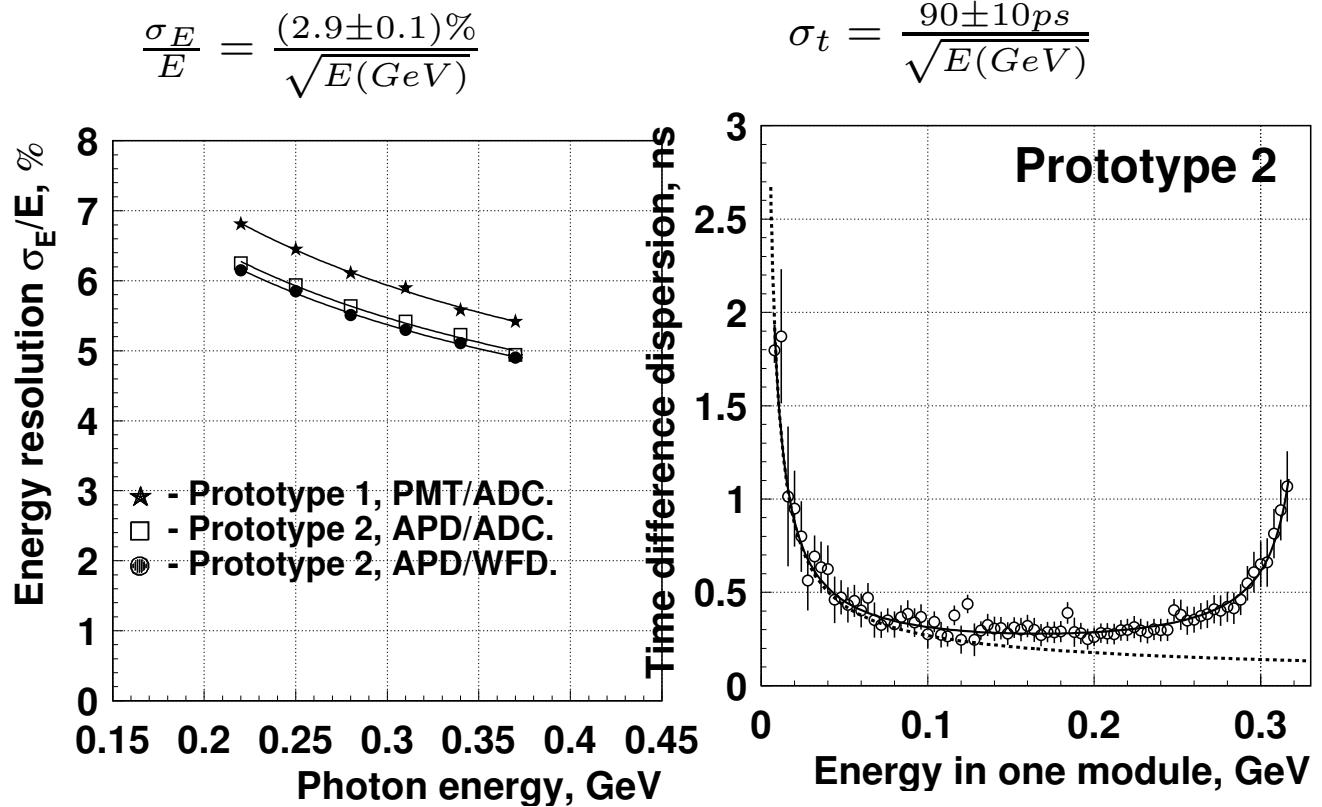
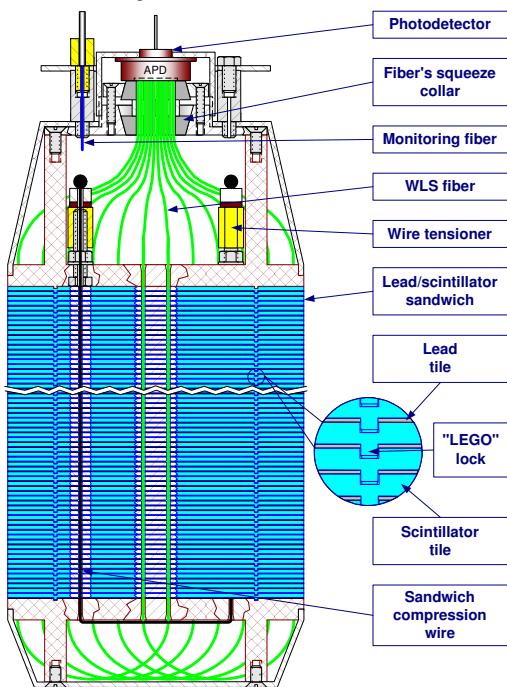
Photon beam. Prototype chamber.



# Shashlyk Calorimeter

- $16X_0$  (18 including preradiator)
- 0.275mm Pb, 1.5mm scintillator
- 24 p.e./MeV

Shashlyk module

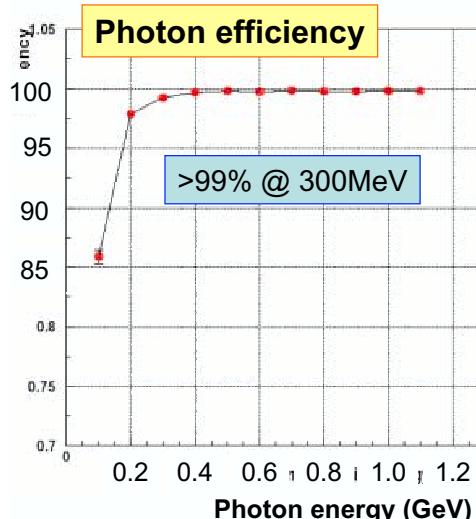
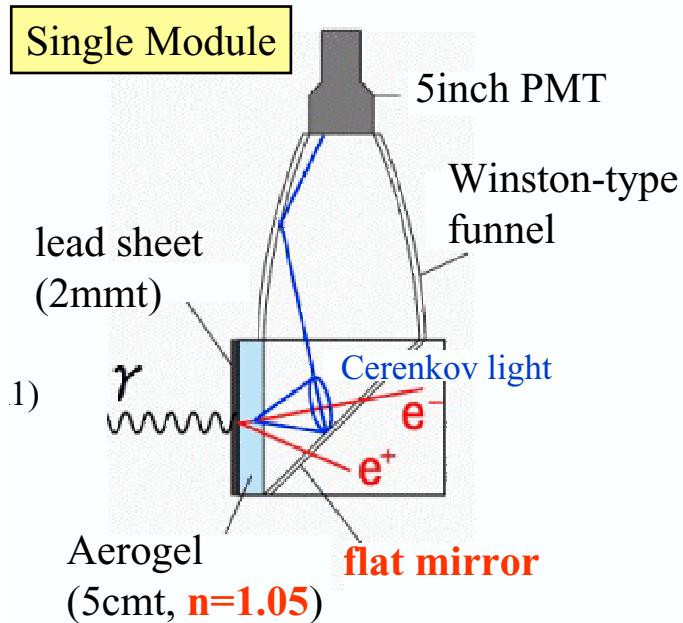


Curves from simulation, not fit.

- In progress: full mechanical design, HV and readout electronics, monitoring system, APD cooling system

# Catcher

## Simulation

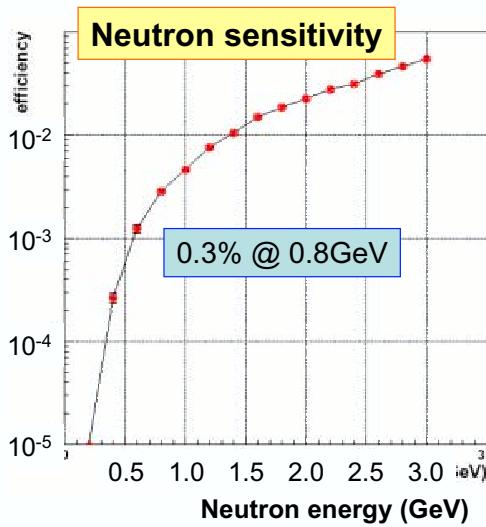


Requirements:

- Photon efficiency  $> 98\%$  at 300 MeV
- Neutron sensitivity  $< 0.3\%$  at 800 MeV

Current effort:

- Veto blindness from photon “flash”, neutrons
- Full-scale prototype test

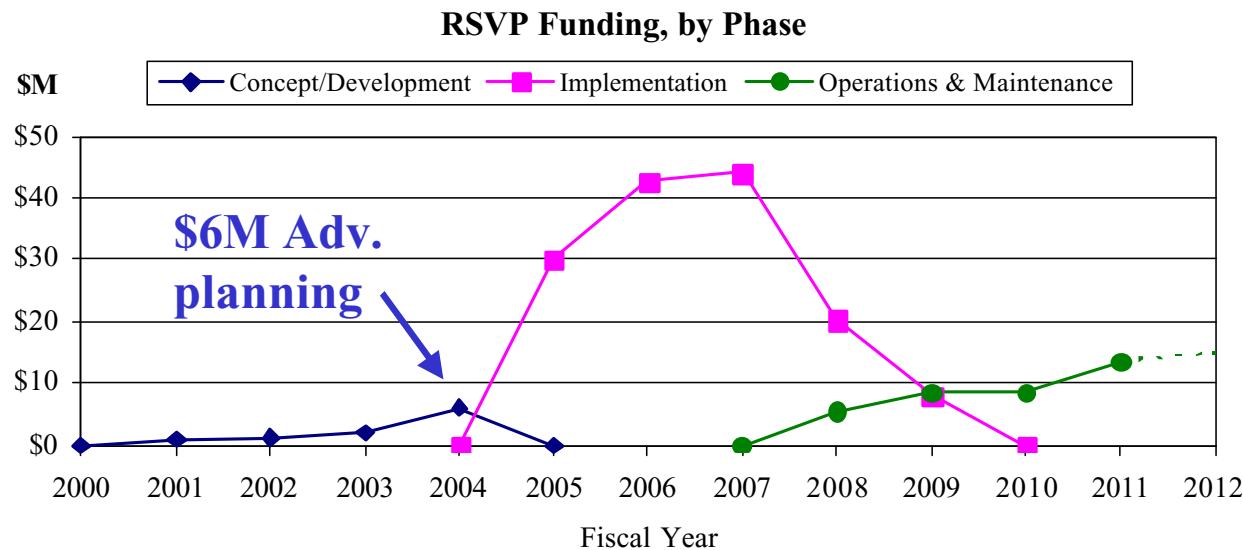


## Conclusion and outlook

- KOPIO R&D phase is winding down. Key features of the concept have been established. Planning for the construction phase is ongoing.
- The RSVP program (KOPIO:  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  and MECO:  $\mu^- N \rightarrow e^- N$ ) was included in the FY05 President's Budget request for a 2005 construction start.  
(<http://www.whitehouse.gov/omb/budget/2005/nsf.html>)
- Near term schedule (2005):
  - Jan: review of signal/background
  - Jan-Feb: review of costs/schedule of each subsystem by local oversight committee
  - Feb: draft Conceptual Design Report
  - Mar: “project startup pre-review”
  - Apr: review by NSF
  - May: report submitted to NSF/NSB

# Conclusion and outlook

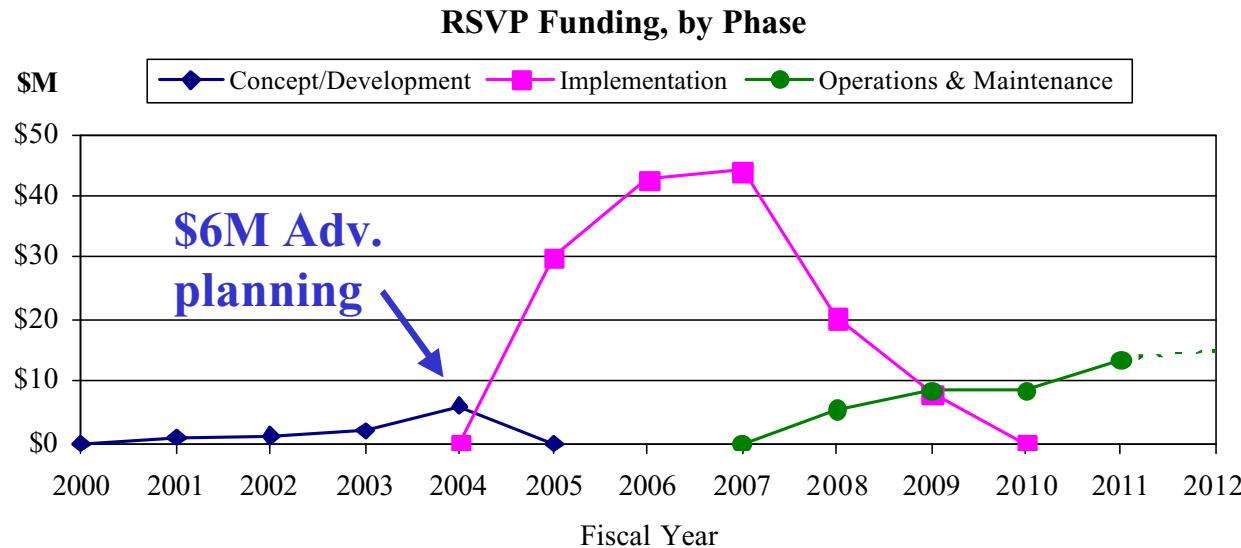
- J. Whitmore (NSF) presentation at BNL (May 04)



- 5 year construction. Test runs starting possibly 2008. Physics running in 2010.

# Conclusion and outlook

- J. Whitmore (NSF) presentation at BNL (May 04)



- 5 year construction. Test runs starting possibly 2008. Physics running in 2010.
- Possible outcome on 50th anniversary of CP violation discovery:

